TITLE:

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AUTHOR(S):

Fujii, Takeshi

CITATION:

Fujii, Takeshi. Kinetic studies on the rearrangement of n-chloroacetanilide under pressure. The Review of Physical Chemistry of Japan 1974, 44(1): 38-55

ISSUE DATE:

1974-09-30

URL:

http://hdl.handle.net/2433/46996

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The Review of Physical Chemistry of Japan Vol. 44 No. 1 (1974)

T. Fujii

KINETIC STUDIES ON THE REARRANGEMENT OF *N*-CHLOROACETANILIDE UNDER PRESSURE

By Takeshi Fujii

The rearrangement of *N*-chloroacetanilide was investigated at pressures of 1, 981, and 2059 atm. The reaction rates in aqueous solution were measured at 15, 25, and 35°C in various hydrochloric acid concentrations. They gave $\Delta V^{\ddagger}$ value of about 5ml/mol and E_a of about 20kcal/mol at 1 atm. The reaction rates in aqueous ethanol solution offered the distance between two ions in the transition state. The distance was increased with increasing pressure from 2.6Å at 1 atm to 3.6Å at 2000 atm. From these evidences it seems that the activated complex in rate determining step is appreciably polar and solvated.

The ratio of *ortho*- and *para*-chloroacetanilide is identical with the k_o/k_p ratio of chlorination of acetanilide. Dependencies of ln (O)/(P) on pressure and temperature gave $\Delta V_o^{\ddagger}-\Delta V_p^{\ddagger}$ value of about 3 ml and $\partial E_{\parallel}$ of 0.74 kcal/mol at 1 atm and suggested that the solvation change was an important factor for isomer distribution.

Introduction

Reaction rates in aqueous solution

The rearrangement of halogenoamine, in which one part of the side chain attached to aromatic compound substitute electrophilically with a hydrogen atom on aromatic ring, is called the Orton rearrangement. *N*-Chloroacetanilide produces a mixture of *ortho*- and *para*-chloroacetanilides by acid catalysis in hydroxylic solvents. Especially with hydrochloric acid, the reaction rate is greatly accelerated.

In the early works the side-chain-to-nucleus migrations of halogen were regarded as true intramolecular rearrangements. But in 1909 Orton and Jones[1] proposed an alternate mechanism of the reaction based on the recognition of the intermediate compound, acetanilide and elemental chlorine.

$$C_6H_5NClCOCH_3 + HCl \underset{(b)}{\overset{(a)}{\rightleftharpoons}} C_6H_5NHCOCH_3 + Cl_2 \xrightarrow[(c)]{} (o\text{- and } p\text{-})\ ClC_6H_4NHCOCH_3 + HCl \qquad (1)$$

Reaction (a) is the rate determining step and reactions (b) and (c) proceed faster than (a). Especially reaction (a) is perfectly rate determining step[2] in aqueous solution. Intramolecular process does not exist in hydroxylic solvents.

In 1927 it was shown[3] that the ratio in which *ortho*- and *para*-chloroacetanilides are formed is

(*Received May 25, 1974*)

1) K. J. P. Orton and W. J. Jones, *J. Chem. Soc.*, 95, 1456 (1902)
2) F. G. Soper, *J. Phys. Chem.*, 31, 1192 (1927)
3) K. J. P. Orton and A. E. Bradfield, *J. Chem. Soc.*, 1927, 986

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the same whether the starting materials are *N*-chloroacetanilide and hydrochloric acid or acetanilide and chlorine.

Olson and his co-worker[4] confirmed the intermolecular process from the result of the isomerization with the hydrochloric acid labelled with radio-active chlorine.

The bimolecular mechanism was supported from the kinetic evidences in the presence of hydrogen chloride and hydrogen bromide and other acids. The reaction is totally of third order, *i. e.*, first with respect to chloramine, first in hydrogen ion, and first in chloride ion.

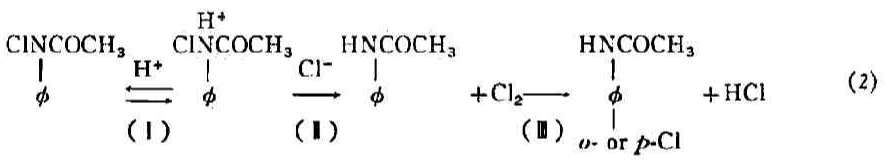
$$\text{Rate}=k[\text{chloramine}][H^+][Cl^-]$$

Harned and Seltz[5], and Soper and Pryde[6] found that observations on the rate agreed with the rate equation expressed by the activities of hydrochloric acid and *N*-chloroacetanilide.

From these evidences Hughes and Ingold[7] regarded reaction (a), the rate determining step, as a bimolecular nucleophilic substitution of halide ion with the chlorine atom of a chloroammonium ion.

In 1956 Harris and Weale[8] examined the effect of high pressure on the velocity of this rearrangement by means of the batch method. They found the retarding effect of pressure and interpreted that in this step the liberation of electrostricted solvent molecules due to the neutralization of the charges will cause $\Delta V^{\neq}$ to be positive.

Finally the following reaction scheme occurs



(2)

where reaction (I) is the preequilibrium and reaction (II) is the rate determining step which is followed by fast chlorination of acetanilide (III).

In aprotic solvents, such as chlorobenzene, halogenoamine rearrangements have evidences for a one-stage intramolecular process and for the effect of light[9,10,11] promoting the transformation of *N*-chloroacetanilide.

Reaction rates in aqueous ethanol

For the reaction between the ions A and B with charges Z_A and Z_B, respectively[12]

$$A^{Z_A}+B^{Z_B}\rightleftharpoons X^{*(Z_A+Z_B)}\longrightarrow \text{products} \qquad (3)$$

the influence of ionic strength on the rate constant in solution is dealt with the Brönsted-Bjerrum equation

4) A. R. Olson, R. S. Halford and J. C. Hornel, *J. Am. Chem. Soc.*, **59**, 1613 (1937)
5) H. S. Harned and H. Seltz, *J.Am. Chem. Soc.*, **44**, 1475 (1922)
6) F. G. Soper and D. R. Pryde, *J. Chem. Soc.*, **1927**, 2761
7) E. D. Hughes and C. K. Ingold, *Quart. Rev.*, **6**, 34 (1952)
8) R. T. Harris and K. E. Weale, *J. Chem. Soc.*, **1956**, 953
9) J. H. Mathews and R. V. Williams, *J. Am. Chem. Soc.*, **45**, 2574 (1923)
10) F. W. Hodges, *J. Chem. Soc.*, **1933**, 240
11) C. C. J. Fontein, *Rec. Trav. Chim.*, **47**, 635 (1928) and cited there J. J. Blanksma, *ibid.*, **21**, 366 (1902)
12) S. Glasstone, K. J. Laidler and H. Eyring, "The Theory of Rate Processes", McGraw-Hill Book Company, Inc., N. Y. and London 1941

$$k=k_0\frac{f_A f_B}{f_X} \tag{4}$$

where k_0 is the rate constant for the infinitely dilute solution, f_i is the activity coefficient of species i.

Here, the Debye-Hückel equation is applied,

$$\ln f_i=-\frac{AZ_i^2\sqrt{\mu}}{1+Ba_i\sqrt{\mu}},$$

neglecting non-electrostatic term and assuming for simplification that the ion size parameter a_i is taken as the mean value of a_A and a_B, then

$$\ln k=\ln k_0+\frac{2AZ_AZ_B\sqrt{\mu}}{1+Ba\sqrt{\mu}}$$

$$A=\frac{(2\pi)^{1/2}N^2\varepsilon^3}{(1000)^{1/2}(DRT)^{3/2}}$$

$$B=\frac{2(2\pi)^{1/2}N\varepsilon}{(1000DRT)^{1/2}}$$

where ε is an electronic charge. N. D. R, and T have the ordinary meanings, and μ is ionic strength of the solution.

According to Guggenheim and Schindler[13], a similar equation is applicable at ionic strength up to 0.1, since the product, Ba. is nearly equal to 1,

$$\ln k=\ln k_0+\frac{2AZ_AZ_B\sqrt{\mu}}{1+\sqrt{\mu}}. \tag{5}$$

It follows from equation (5) that the plot of $\ln k$ against $\frac{\sqrt{\mu}}{1+\sqrt{\mu}}$ should give a straight line of slope $2AZ_AZ_B$ and an intercept at $\frac{\sqrt{\mu}}{1+\sqrt{\mu}}=0$ is $\ln k_0$.

Scatchard[14], using statistical mechanics, calculated the concentration of the transition state directly from equations given by Debye and Hückel. This concentration is taken as proportional to the bulk concentration of A ions multiplied by the average concentration of B ions at a distance r from an A ion, where r is the distance between A and B in the transition state. When ionic strength of the medium is zero, the concentration is reduced to

$$(C_X)_0=K^s(C_A)_0(C_B)_0\ \exp\left(-\frac{\varepsilon^2Z_AZ_B}{DkTr}\right). \tag{6}$$

From equation (6) Scatchard also showed the effect of changing solvent on the concentration of the transition state in so far as that effect was due to changing dielectric constant of a homogeneous medium. The Scatchard treatment being applied, it is possible to drive the next equation from equations (4) and (5)

$$\ln k_0=\ln k_{01}+\frac{\varepsilon^2Z_AZ_B}{kTr}\left(1-\frac{1}{D}\right), \tag{7}$$

where D is the dielectric constant in the medium in question and k_{01} is the rate constant in the infinitely dilute, *i. e.*, ideal, gas where dielectric constant is unity.

Thus the rate constant, extrapolated to zero ionic strength, is a function of the dielectric constant

13) E. A. Guggenheim and T. D. Schindler, *J. Phys. Chem.*, **38**, 543 (1934)

14) G. Scatchard, *Chem. Rev.*, **10**, 229 (1932)

of the medium. The plot of ln k_0 vs. $1/D$ should be linear with a slope of $\varepsilon^2 Z_A Z_B/kTr$.

On Brönsted's theory the reaction scheme (2) offers a rate constant as follows.

$$k_{obs}=K_I k_{II}\frac{f_H f_{Cl} f_N}{f_X} C_H C_{Cl} \tag{8}$$

$$=K_I k_{II}\frac{f_N}{f_X} a_H a_{Cl} \tag{9}$$

where K_I is the equilibrium constant of process (I) and k_{II} is the rate constant of process (II) and subscript N denotes *N*-chloroacetanilide. Corresponding to equation (5) reaction (2) gives the next equation (10)

$$\ln k=\ln k_0+\frac{2AZ_H Z_{Cl}\sqrt{\mu}}{1+\sqrt{\mu}}, \tag{10}$$

since $k=k_{obs}/C_H C_{Cl}$. $k_0=K_I k_{II}$, and $Z_N=0$.

From equation (6) the concentration of the transition state at zero ionic strength of process (II) is given by equation (11)

$$(C_X)_0=K''(C_M)_0(C_{Cl})_0 \exp\left(-\frac{\varepsilon^2 Z_M Z_{Cl}}{DkTr}\right), \tag{11}$$

where M denotes protonated *N*-chloroacetanilide shown in reaction (2).
Also $(C_M)_0=K_I(C_H)_0(C_N)_0$, for $Z_N=0$. Then we obtain

$$(C_X)_0=K''K_I(C_N)_0(C_H)_0(C_{Cl})_0 \exp\left(-\frac{\varepsilon^2 Z_M Z_{Cl}}{DkTr}\right). \tag{12}$$

Corresponding to equation (7) it is found that

$$\ln k_0=\ln k_{01}+\frac{\varepsilon^2 Z_M Z_{Cl}}{kTr}\left(1-\frac{1}{D}\right). \tag{13}$$

Usually the effect of pressure on reaction rate is indicated quantitatively by $\Delta V^{\neq}$[15] which is equal to $-RT\partial \ln k/\partial P$. In the case of reaction (2) a modification of equation (9) as $k'=k_{obs}/a_H a_{Cl}$ $=K_I k_{II} f_N/f_X$ leads to the next equation, regarding the change of f_N/f_X depending on ionic strength as negligibly small over the range in $\mu=0.1\sim0.3$

$$\Delta V^{\neq}=\Delta V_I+\Delta V_{II}^{\neq}. \tag{14}$$

where ΔV_I and $\Delta V_{II}^{\neq}$ are volume changes accompanied by the processes (I) and (II), respectively in reaction (2).

$\Delta V^{\neq}$ and the pressure dependence of r will offer information about the behavior of the transition state under pressure.

Distribution of the product isomers

N-Chloroacetanilide rearranges with hydrochloric acid catalysis in aqueous solution, and finally produces *ortho*- and *para*-chloroacetanilides. The reaction process (III) consists of two competitive reactions, *i. e.*, the *ortho*-forming and *para*-forming paths. The ratio of the products is independent of the time, and so satisfies Wegscheider's test[16] for the simultaneity of two reactions of the same order;

15) S. D. Hamann, "Physico-Chemical Effect of Pressure", Butterworths Scientific Publication, London, 1957
16) R. Wegscheider, *Z. phys. Chem.*, **30**, 593 (1899)

then the ratio of the reaction products is reduced to the ratio of the rate constants for each product.

The effect of pressure on the ratio of the products gives δ ($\Delta V_{\mathrm{I}}^{*}$) value, the difference of the activation volumes for the competitive reactions, although the individual activation volumes themselves are not known.

Similarly the temperature dependence of the product ratio gives the difference of the activation energy between the competitive reactions.

With respect to the effect of pressure on the orientation of electrophilic aromatic substitutions. Gonikberg[17] showed that at high pressure the sterically strained isomer was yielded in a higher proportion than it was at ordinary pressure. Coillet and Hamann[18] have shown that not only the steric factor, but also the changes of dielectric constant and solvation are important in nitrations. The last two factors may alter the distribution of electric charge around the benzene ring.

Apparatus and Reagents

Apparatus

The high pressure apparatus is illustrated in Figs. 1 and 2, where we can take out samples continuously without release of the pressure. The reaction vessel is a 50m*l* cut-off glass hypodermic syringe which is contained in the pressure vessel made of stainless steel and designed for 3 kb.

The outlet of the syringe is connected to a stainless steel capillary sampling tubing by means of a stainless steel union. The lower part of the union is attached to the syringe by araldite. And an O-ring isolates the reaction solution from the hydraulic oil. The upper part of the union is held to the capillary tubing by araldite and can give the force on the neoprene seal. The capillary tube passes through the pressure tubing and is fixed to it at the upper end. The sampling valve is also made of stainless steel. When the valve is opened the reaction solution flows out and is collected in a suitable vessel. The head of the pressure vessel is sealed by an O-ring. Pressure is generated by a hand pump with a screw injector and an intensifier which is able to intensify about 15 times. A primary pressure was measured by a Bourdon tube. The pressure in the reaction vessel, a secondary pressure, was measured by means of a manganin gauge connected to the junction block. The manganin gauge was calibrated against the free piston gauge. The pressure vessel was immersed in a thermostatted bath. Immediatelly after the sampling the oil was pumped into the pressure vessel to compensate the loss of the fluid.

The samples were taken out for analysis, after allowing the time for temperature equilibration. About 6 samples of 3 ml each could be taken in a run.

Reagents

N-Chloroacetanilide was prepared from extra-pure reagent grade acetanilide and bleaching

17) M. G. Gonikberg, "Chemical Equilibrium and Reaction Rate at High Pressure", Japanese translated by Y. Ogo, Nikkan Kogyo Shinbunsha, Tokyo (1972)

18) D. W. Coillet and S. D. Hamann, *Nature*, 200, 166 (1963)

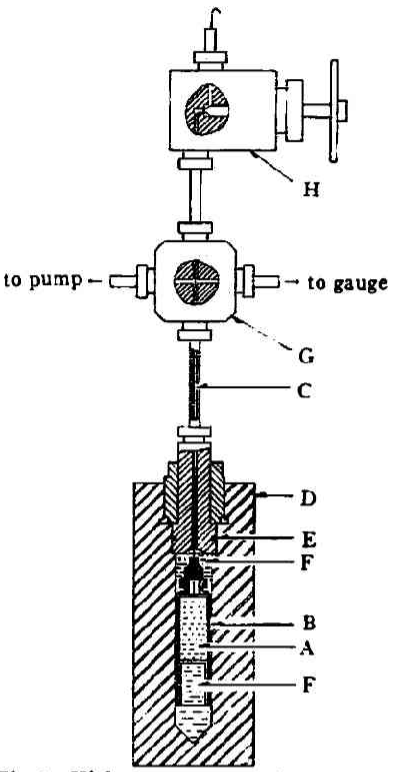


Fig. 1 High pressure apparatus for kinetic measurements
A: Reaction mixture.
B: Reaction vessel,
C: Sampling capillary,
D: Pressure vessel,
E: "O"-ring,
F: Hydraulic oil,
G: Junction block,
H: Sampling valve

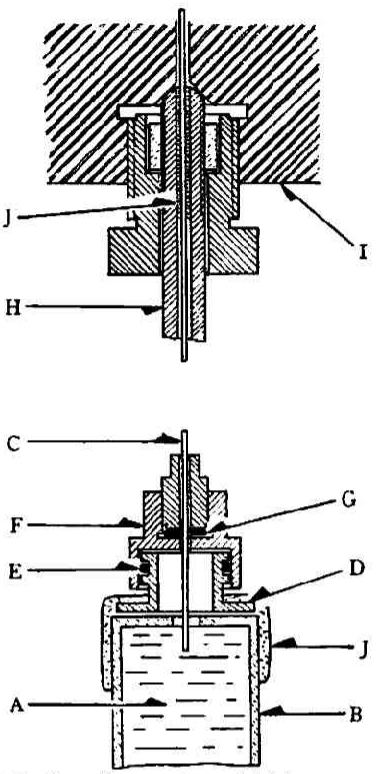


Fig. 2 Sampling system of high pressure apparatus
A: Reaction mixture,
B: Hypodermic syringe,
C: Sampling capillary,
D: Lower part of connector,
E: "O"-ring,
F: Upper part of connector
G: Neoplene seal,
H: Pressure tube,
I: Sampling valve,
J: Araldite

powder solution basified by sodium bicarbonate according to Hodges.[10] The compound was dried on phosphor pentoxide and preserved in a desicator over silica gel. The crystals were white and melted at 90~91°C.

ortho- and *para*-Chloroacetanilide were recrystallized from methylenechloride solution of guaranteed reagent grade.

Ethanol used to vary the dielectric constant of the medium was of the guaranteed reagent grade dried by reflux over calcium oxide.

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Procedure

Reaction rates in aqueus solution

The concentration of *N*-chloroacetanilide solutions for all the rate experiments were about 0.002 mol/*l*. A fixed quantity of *N*-chloroacetanilide was dissolved and 1.0 N HCl was added to the results in 0.1, 0.2, and 0.3 N solutions.

The mixture was cooled slightly below the reaction temperature and then introduced to the reaction vessel when the course of the reaction was followed under pressure. The precooling compensates the heat generated by compression and quenches the reactions until pressure is applied.

The reactions were carried out under pressure at 15, 25, and 35°C. In measuring the reaction rates, the first 1 m*l* of the sample solution was rejected so that the sample came wholly from the syringe, and 3 m*l* were pippetted.

The concentrations were determined by titration[19] with 0.002 mol/*l* thiosulphate which reduced the iodine liberated from 10m*l* of 0.1 N potassium iodide, using starch as an indicator.

As already shown in the previous section, the reaction is of the first order with respect to the substance rearranging. The observed rate constants, k_{obs}, contain the catalyst activity as a factor. To obtain the true first-order rate constant, k', we must divide the observed constants by the square of the activity of the catalyst at the pressure and temperature of the experiment.

An expression for the activity coefficients of hydrochloric acid in water at high pressure is given by Harned and Owen[20].

The activity coefficient for 0.1 and 0.2 N HCl at 15, 25, and 35°C at ordinary pressure were obtained from Harned and Owen, and the value for 0.3N HCl at 25°C 1 atm was from "International Critical Table", Table 1 shows the actually used values.

Table 1 Activity coefficients of HCl

Temp. °C	HCl N	Pressure, atm		
		1[a]	981[c]	2059[c]
35	0.1	0.7918	0.7970	0.8002
	0.2	0.7604	0.7675	0.7712
25	0.1	0.7964	0.8016	0.8048
	0.2	0.7667	0.7738	0.7781
	0.3	0.7563[b]	0.7649	0.7701
15	0.1	0.8000	0.8071	0.8084
	0.2	0.7717	0.7789	0.7832

a) H. S. Harned and B. B. Owen, ref. 20)
b) *Int.Crit. Table*, 7, 233
c) calculated by the Harned-Owen equation, ref. 20)

19) A. C. D. Rivett, *Z. phys. Chem.*, **82**, 201 (1913)
20) H. S. Harned and B. B. Owen, "The Physical Chemistry of Electrolytic Solutions", Reinhold, N. Y., 1958

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Rates in aqueous ethanol

The concentration of *N*-chloroacetanilide was about 0.002 mol/*l*. The dielectric constant of the solution were varied with dried ethanol to 4, 8, 12, and 16 wt%. The ionic strength of the solution were made 0.02, 0.04, 0.06, and 0.10 by the addition of HCl. The reactions were performed at 25°C under 1, 981, and 2059 atm. The first order rate constants under pressure with respect to *N*-chloroacetanilide were observed by the batch method in the cases of 0.02, 0.04, 0.06 N HCl. The compressions of mixed solvents were obtained by the interpolation of the results of Moesveld[21]. The rate constants and the ionic strengths and the concentrations of catalysts were corrected for the compression using the values of Table 2. The dielectric constants of various compositions of ethanol-water mixed solvent

Table 2 Volume factor, β, by compression for water[a] and aqueous ethanol[b] at 25°C

Ethanol wt%	Pressure, atm 1	981	2059
0	1.000	1.040	1.077
3.985		1.039	1.074
8.022		1.038	1.072
12.14		1.037	1.071
16.27		1.037	1.070

a) Interpolation of Bridgeman's data, *Intern. Crit. Table*, 3, 40
b) Interpolated and calculated by Moesveld, ref. 21)

at 1 atm and 25°C were obtained by the interpolation of Amis' data[22] and then those under pressure were calculated and extrapolated by means of the equation of Owen *et al*[23,24]. The dielectric constants obtained by such a treatment are shown in Table 4. The least-square method was used to obtain slopes and intercepts, $\log k_0$, of $\log k$ vs. $\frac{\sqrt{\mu}}{1+\sqrt{\mu}}$ plots. At each pressure the $\log k_0$ against $\frac{1}{D}$ were plotted and the slopes were obtained by the least-square method.

Table 3 $\sqrt{\mu}/(1+\sqrt{\mu})$ values for various solvents at 25°C, calculated by using ionic strength corrected for various compressions

HCl N	Pressure, atm 1	981	2059	
	for all solvents		for water	for aqueous ethanol
0.02	0.1239	0.1259	0.1281	0.1276
0.04	0.1667	0.1694	0.1720	0.1714
0.06	0.1968	0.1999	0.2029	0.2022
0.10	0.2402	0.2439	0.2473	0.2465

21) A. L. T. Moesveld, *Z. phys. Chem.*, 105, 442 (1923)
22) E. S. Amis and V. K. La Mer, *J. Am. Chem. Soc.*, 61, 905 (1935)
23) B. B. Owen, R. C. Miller, C. E. Milner and H. L. Cogan, *J. Phys. Chem.*, 65, 2065 (1961)
24) P. J. Pearce and W. Strauss, *Austr. J. Chem.*, 21, 2127 (1963)

Table 4 Used values of dielectric constants for water and aqueous ethanol at 25°C

Ethanol wt%	Pressure, atm 1	981	2059
		(a) D	
0	78.4	81.8	85.1
3.985	76.1	79.5	82.7
8.022	73.8	77.0	80.1
12.14	71.4	74.6	77.6
16.27	69.0	72.1	75.0
		(b) $10^2/D$	
0	1.28	1.22	1.17
3.985	1.31	1.26	1.21
8.022	1.36	1.30	1.25
12.14	1.40	1.34	1.29
16.27	1.45	1.39	1.33

Determination of the isomer distribution

The sample solutions used for the product analysis were about 0.003 mol/l with respect to *N*-chloroacetanilide and 0.3 N with respect to hydrochloric acid.

The reactions under pressure were carried out in a 10 ml hypodermic syringe with a teflon stopper.

After 24 hours, the samples were taken out for the analysis by releasing the pressure. Up to this time the reaction was complete with 0.3N HCl even at 15°C.

The products were extracted from the aqueous solution with 10 ml each of methylene chloride for 6 times. The extract was washed with distilled water for 4 times and then concentrated up to about 1 ml.

The isomer mixture was separated to each component by the silica gel thin layer with the effluent of benzene : acetone = 7: 1 by volume. The positions of the compounds were decided by the treatment with I_2 vapor. The silica gel containing the compound was carefully gathered with a microspatula on a glass filter and the compound was washed with guaranteed reagent grade ethanol for about 8 times into a 50 ml volumetric flask.

The concentrations of products were determined from U. V. spectrum of the solution. *ortho*- and *para*-Chloroacetanilide had the optical absorption with peaks at 239 mμ and 247 mμ respectively and the extinction coefficients of 0.90×10^4 and 1.89×10^4 cm^{2}mol^{-1} at respective absorption maxima.

Results

Rates in aqueous solution

The first order reaction rates were observed with respect to *N*-chloroacetanilide and the first order rate constants, k_{obs}, were calculated graphically in the usual manner.

Table 5 The square of the mean activity of HCl based on Table 1

Temp. °C	HCl N	$a^2_{HCl} \times 10^2$ Pressure, atm 1	981	2059
35	0.1	0.6269	0.6352	0.6402
	0.2	2.313	2.356	2.382
25	0.1	0.6343	0.6426	0.6477
	0.2	2.351	2.395	2.422
	0.3	5.148	5.266	5.337
15	0.1	0.6400	0.6514	0.6535
	0.2	2.382	2.427	2.454

Table 6 Effect of pressure and temperature on the rate constant k', $\Delta V^{\ddagger}$, E_a, and $\Delta S^{\ddagger}$

Temp. °C	HCl N	k', min^{-1} Pressure, atm 1	981	2059	$\Delta V^{\ddagger}$ ml
35	0.1	0.502	0.406	0.351	
	0.2	0.497	0.406	0.302	
	mean	0.500	0.406	0.327	6.5
25	0.1	0.164	0.136	0.116	
	0.2	0.166	0.135	0.116	
	0.3	0.166	0.138	0.114	
	mean	0.165	0.136	0.115	5.3
15	0.1	0.0534	0.0447	0.0388	
	0.2	0.0538	0.0465	0.0386	
	mean	0.0536	0.0456	0.0387	4.0
E_a, kcal/mol		19.7	19.3	18.8	
$\Delta S^{\ddagger}$, cal/deg mol		−6.17	−7.92	−9.92	

The true first order rate constants were obtained by dividing the observed constants by the square of the mean activity of hydrochloric acid at the experimental condition shown in Table 5. The rate constants are listed in Table 6.

The true first order rate constants were fitted to the following equation as shown in Fig. 3,

$$\log k' = aP^2 + bP + c.$$

The reactions were retarded by pressure and the positive activation volumes were calculated from the slope at 1 atm, namely $\Delta V^{\ddagger} = -2.303\,(2aP+b)RT$. The values are summarised in the last column of Table 6. The activation energies were also obtained from the Arrhenius plot shown in Fig. 4. The values of the activation energies and the activation entropies are listed below the broken line in Table 6.

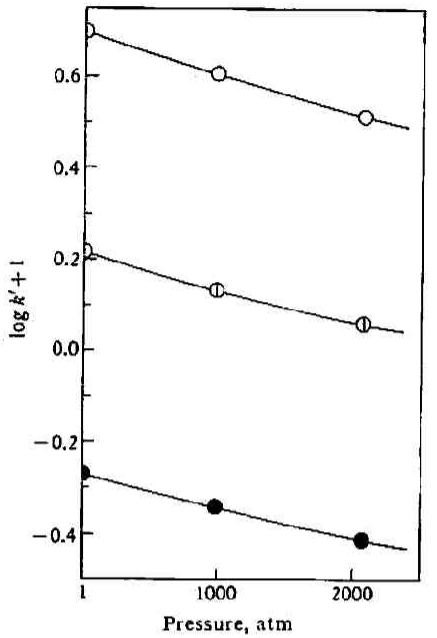


Fig. 3 Variation of the true first order rate constant with pressure,
○: 35°C, ◑: 25°C,
●: 15°C

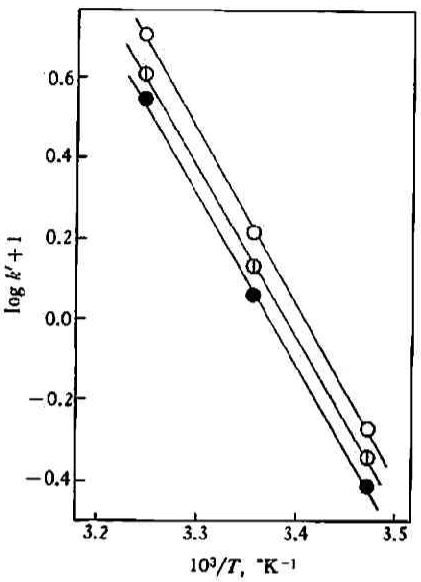


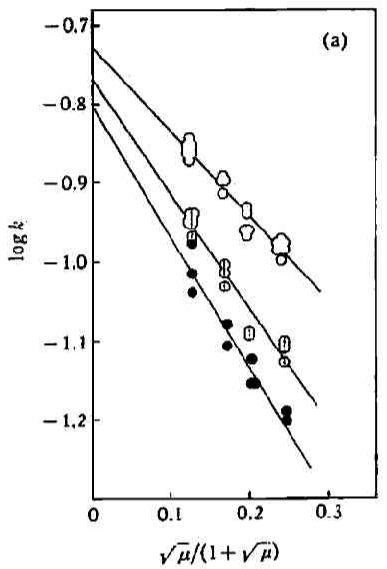
Fig. 4 Arrhenius plot of the true first order rate constant at various pressures,
○: 1 atm, ◑: 981 atm,
●: 2059 atm

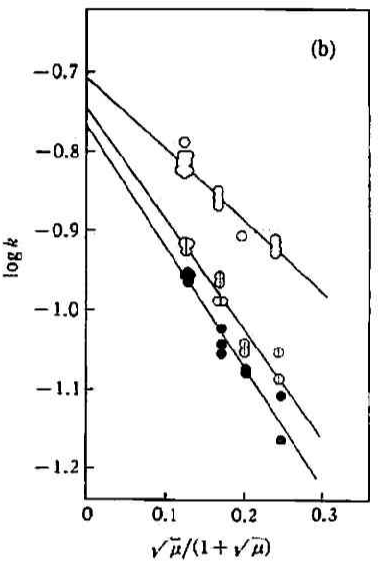
Table 7 β^3C^2 at 25°C

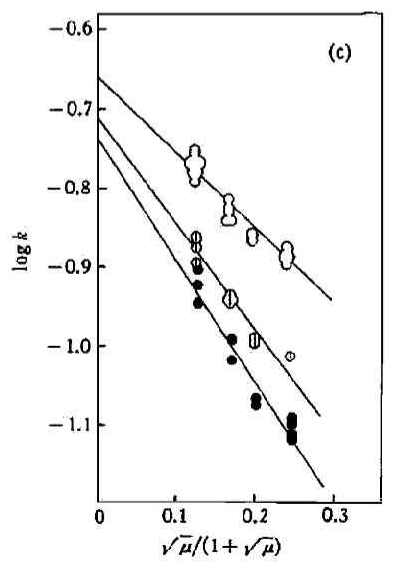
HCl N	Ethanol wt% 0	3.985	8.022	12.14	16.27	
			(a) 1 atm			×10^X
0.02			4.000			X=−4
0.04			1.600			−3
0.06			3.600			−3
0.10			1.000			−2
			(b) 981 atm			
0.02	4.500	4.488	4.476	4.464	4.460	−4
0.04	1.800	1.795	1.790	1.786	1.784	−3
0.06	4.050	4.039	4.028	4.018	4.014	−3
0.10	1.125	1.122	1.119	1.116	1.115	−2
			(c) 2059 atm			
0.02	4.996	4.952	4.928	4.912	4.904	−4
0.04	1.998	1.981	1.971	1.965	1.962	−3
0.06	4.496	4.457	4.435	4.421	4.414	−3
0.10	1.249	1.238	1.232	1.228	1.226	−2

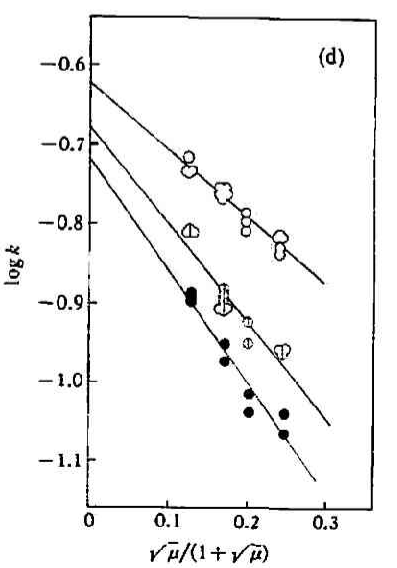
Reaction rate in aqueous ethanol

The observed rate constant was divided by β^3C^2 to manifest the activity coefficients according to equation (8), where β was the volume factor by compression and C was the concentration of the catalyst at 1 atm. β^3C^2 are listed in Table 7.









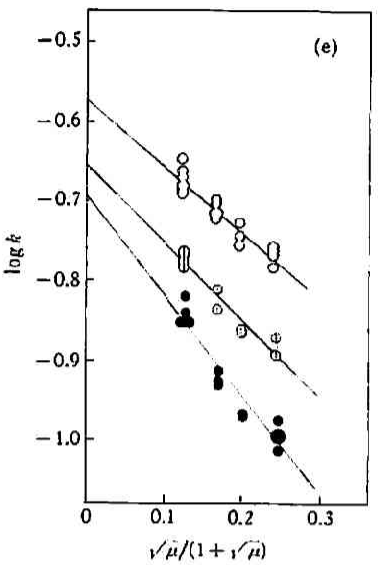


Fig. 5 Plot of log k vs. $\sqrt{\mu}/(1+\sqrt{\mu})$. Lines were drawn by the least-square method. Area of each place corresponds to the nomber of runs.
(a) aqueous solution, (b) 3.985wt% ethanol,
(c) 8.022wt% ethanol, (d) 12.14wt% ethanol.
(e) 16.27wt% ethanol
○: 1 atm, ⓘ: 981 atm, ●: 2059 atm

As shown in Figs. 5, log k at various wt% of ethanol were plotted against $\frac{\sqrt{\mu}}{1+\sqrt{\mu}}$, and the slopes and the intercepts were calculated by the least-square method. Log k_0 thus obtained are listed in Table 8. In the case of aqueous solution at 1 atm the experimental value of the slope was -1.07, and the calculated value based on the Debye-Hückl equation was -1.02.

At each pressure log k_0 against $\frac{1}{D}$ were shown in Figs. 6, and the straight lines were also obtained by the least-square method. Then the slope and r are listed in Table 9. The straight lines correspond to $r=2.6$, 3.4, and 3.6Å at 1, 981, and 2059atm according to the Scatchard equation.

Table 8 Rate constants extrapolated to zero ionic strength under pressure at 25°C

Ethanol wt%	log k_0 Pressure. atm 1	981	2059
0	−0.7271	−0.7681	−0.8024
3.985	−0.7063	−0.7453	−0.7673
8.022	−0.6596	−0.7106	−0.7372
12.14	−0.6215	−0.6773	−0.7170
16.27	−0.5718	−0.6530	−0.6921

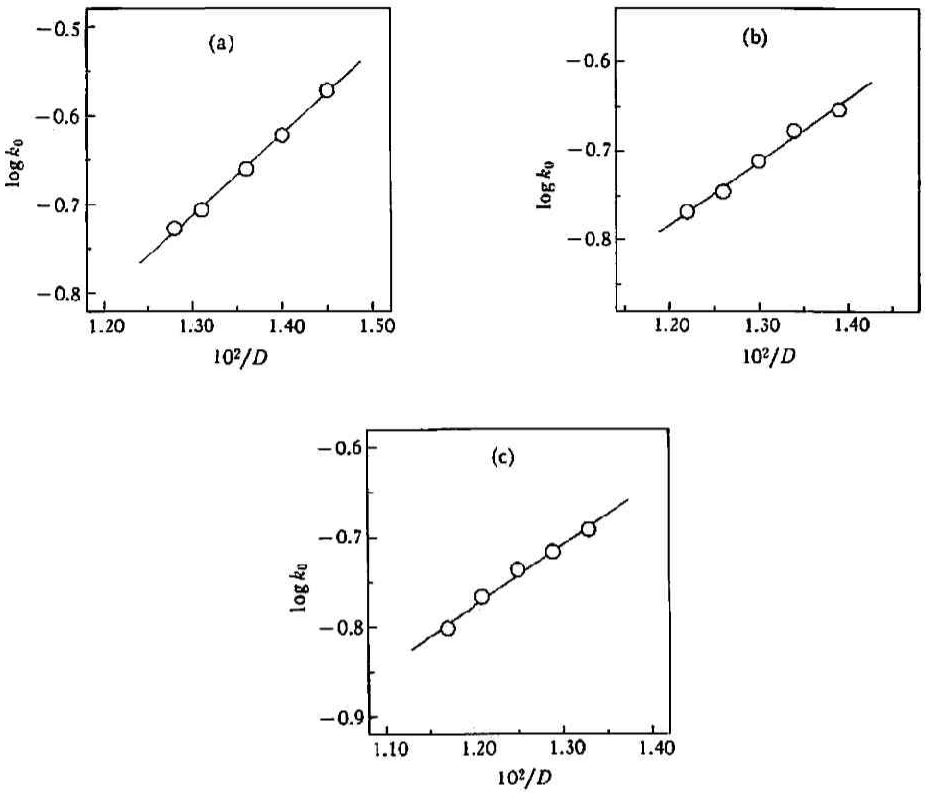


Fig. 6 Change of the rate constant at zero ionic strength with the dielectric constant of the medium at 25°C. Lines were drawn by the least-square method.
(a) 1 atm, (b) 981 atm, (c) 2059 atm

Table 9 Effect of pressure on the distance between ions in the transition state

Pressure atm	Slope $\times 10^{-2}$	r Å
1	0.9225	2.64
981	0.7080	3.44
2059	0.6775	3.59

Distribution of isomers

The relative yield of the products under various conditions are listed in Table 10, where O denotes *ortho*-chloroacetanilide and P denotes *para*-chloroacetanilide. An increase of pressure and temperature tends to favor the formation of *para*-chloroacetanilide. The blank test whether mutual conversions of the products, *i. e.*, *ortho*-to-*para*- and *para*-to-*ortho*-chloroacetanilide, due to pressure

Table 10 Fraction of *o*- and *p*-chloroacetanilide in aqueous solution

Temp. °C	Pressure					
	1 atm		981 atm		2059 atm	
	O	P	O	P	O	P
35	0.507	0.493	0.479	0.521	0.443	0.557
25	0.498	0.502	0.466	0.534	0.434	0.566
15	0.486	0.514	0.454	0.546	0.420	0.580

and hydrochloric acid occured gave no evidence of such conversions to the utmost of the thin layer chromatography.

The concentrations of the products are given by the following equations

$$[O]=\int_0^t k_O[A][Cl_2]dt \quad \text{and} \quad [P]=\int_0^t k_P[A][Cl_2]dt \tag{15}$$

where A is acetanilide at process (III) in equation (2). For a simultaneous reaction the ratio of the products can be written as $\frac{O}{P}=\frac{k_O}{k_P}$. Then we obtain the following expression for pressure effect on the ratio of products,

$$-RT\frac{\partial \ln(O/P)}{\partial P}=-RT\frac{\partial \ln(k_O/k_P)}{\partial P}=\Delta V_O^{*}-\Delta V_P^{*}=\delta(\Delta V_{III}^{*}). \tag{16}$$

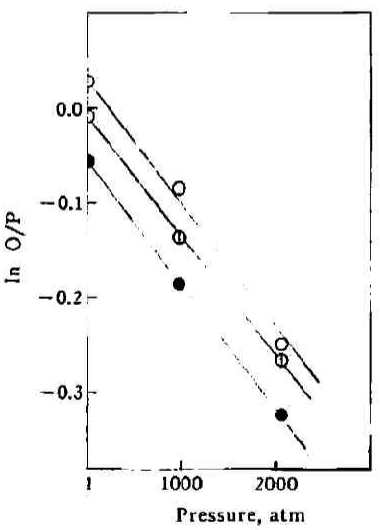


Fig. 7 Pressure effect on the fraction of product isomers
○: 35°C, ◐: 25°C,
●: 15°C

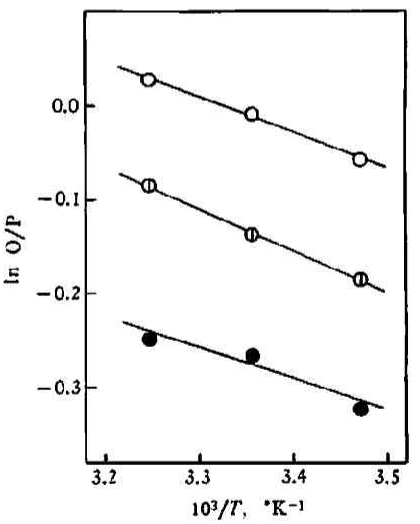


Fig. 8 Arrhenius plot of the fraction of product isomers
○: 1atm, ◐: 981 atm,
●: 2059 atm

The values of $\delta(\Delta V_{III}^{*})$ and $\delta E_{III}=E_O-E_P$ were obtained graphically as shown in Figs. 7 and 8. The results are listed on the positions under the condition described in Table 11. The difference of the entropy change, $\delta(\Delta S_{III}^{*})=\Delta S_O^{*}-\Delta S_P^{*}$, was about 2.5cal/deg mol at 25°C 1 atm.

Table 11 Differences of the activation volumes $\delta(\Delta V^{*}_{\mathrm{II}})$, anddifferences of the activation energies, δE_{II}, for the process III of reaction (2) calculated from the values of Table 10

Temp. °C	$\ln\frac{O}{P}$ Pressure, atm 1	981	2059	$\delta(\Delta V^{*}_{\mathrm{II}})$ ml
35	0.028	−0.084	−0.249	2.4
25	−0.008	−0.136	−0.266	3.3
15	−0.056	−0.185	−0.323	4.0
δE_{II}, kcal/mol	0.738	0.965	0.654	

Discussion

Rates in aqueous solution

The obtained rate constant, $27.4\times10^{-4}\mathrm{sec}^{-1}$, and the activation volume, 5.3 m*l*, at 25°C 1 atm agree with the values of Harris and Weale[8], $27.3\times10^{-4}\mathrm{sec}^{-1}$ and 7.2m*l*, respectively. The activation energy of this work agree with the value, 20.6kcal/mol, reported by Percival and La Mer[26].

As shown in Table 6, the constancy of $\frac{k_{\mathrm{obs}}}{a_{\mathrm{HCl}}^{2}}$ at each pressure to within the experimental error supports the assumption that the activity coefficient ratio $\frac{f_{\mathrm{N}}}{f_{\mathrm{X}}}$ vary little over the acid range examined (0.1∼0.3N).

Although S_{v} and S_{k} at 15 and 35°C will differ from those of 25°C, the resulting activity coefficients calculated at 25°C will give approximately real values for 15 and 35°C. The effect of pressure on the activity coefficients of the catalyst will usually be of a lower order of magnitude than the effect of pressure on rate constants.

Equation (14) shows the contribution of the volume differences which belong to respective processes of reaction (2) to the observed ΔV^{*}. For the protonation of amines, ΔV are summarized by Whalley[27] and allow us to estimate ΔV_{I} about $-5\sim-10$m*l*/mol. From ΔV for charge neutralization $\Delta V_{\mathrm{II}}{}^{*}$ is estimated as about 20m*l*/mol. Using equation (14), ΔV^{*} is estimated as about $+10\sim15$m*l*/mol. The observed value of ΔV^{*} is somewhat smaller than this estimated value. This fact may suggest that the activated complex of process (II) has somewhat ionic charactor or is desolvated incompletely.

From Table 6 it is shown that $\partial(\Delta S^{*})/\partial P$ is negative. Already it is found that a hydration number of an ion and a radius of a hydrated ion are not changed by pressure[28]. In so far as that appropriate parameters of reactant ions such as the hydration numbers are kept constant under pressure, this negative $\partial(\Delta S^{*})/\partial P$ is attributed to the increase of the extent of hydration of the transition state with

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27) E. Whalley, Advances in Physical Organic Chemistry, Vol. 2, p. 93, Academic Press, 1964
28) E. Inada, K. Shimizu and J. Osugi, *This Journal*, 42, 1 (1972)

increasing pressure.

Rates in aqueous ethanol

The formula of Owen *et al*[23], is fitted for the dielectric constant of water under pressure up to 1000 bar. It seems unreasonable to estimate the dielectric constant of water by extrapolation to 2000 atm by using this equation. But the estimated value of water by this equation may cause rather small error. The value of 85.11 estimated by extrapolation of the formula of Owen *et al.* to 2059 atm agrees well with that of 85.12 obtained by the Tait type equation according to Owen and Brinkley[29]. Parameters A and B in the Tait type equation, $\frac{D_1}{D_p}=1-AD_1\log\frac{B+P}{B+1}$, is $A=0.005181$ and $B=3616$ atm as determined from the dielectric constant at ordinary pressure and 981 atm, *i. e.*, $D_1=78.36$ and $D_p=81.82$. Pearce and Strauss[24] found that the dielectric constant for dioxane-water mixtures under pressure could be estimated from the values of the mixture at atmospheric pressure and the assumption that the proportional change was similer under pressure to that at 1 atm by using simple linear interpolation. They also found that the Owen-Brinkley equation was applicable to liquid mixtures.

Fig. 5 shows that log k at 25°C conforms to the Brönsted-Debye primary salt equation for $\mu=0.02\sim0.1$, approaching a limitting slope corresponding to $Z_AZ_B=-1$. Accordance of the experimental value of the slope, -1.07, with the calculated value, -1.02, in aqueous solution at 1 atm properly accepts as good evidence for the postulated ionic mechanism (2).

As shown in Fig. 6 the positive slopes of these lines still agree with the electronic charge-type of the rate determining step in reaction (2).

The obtained value of r, equal to 2.6Å at 1 atm, is entirely reasonable. In transition state a Cl-Cl bond is going to form newly where the bond length must be longer than that of chlorine molecule, 1.99 Å, and be shorter than 6 Å, the twice of ionic radius of chloride ion, or than 7~9Å, the sum of ionic radius of chloride and that of ammonium ion[30].

According to Table 9 the distance r between ions in the transition state in process (II) of reaction (2), calculated by using the theoretical equation of Scatchard, is increased by pressure. The transition state consists of oppositely charged two ions, and it is regarded as a dipole. The increase of the polarity of the transition state due to the increasing distance with pressure lead to the increase of electrostricted volume, thus increase of pressure results in increase of the degree of solvation of the transition state. Pressure actually leads to the shift of the transition state position in the direction of reactants along the reaction coordinate. The evidence of Table 9 coincides with the fact that an increase of pressure results in a decrease of positive ΔV^* as followed from great depression of the curves in Fig. 3 and that an increase of pressure also results in an increase of the magnitude of negative ΔS^*, which means an increase of the degree of hydration, as previously stated.

From the point of view of compressibility Table 9 gives the transition state a negative compressibility. For isoprene dimerization Benson and Berson[31] calculated ΔV^* on the assumption that the

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M. Nakahara, K. Shimizu and J. Osugi, *This Journal*, **42**, 12 (1972)

29) B. B. Owen and S. R. Brinkley, Jr., *Phys. Rev.*, **64**, 32 (1943)

30) J. Kielland, *J. Am. Chem. Soc.*, **59**, 1675 (1937)
E. R. Nightingale, Jr., *J. Phys. Chem.*, **63**, 1381 (1959)

31) S. W. Benson and J. A. Berson, *J. Am. Chem. Soc.*, **84**, 152 (1962)

transition state compressibility was similar to that of the normal molecule. On the other hand, Walling and Tanner[32] required an abnormally lower compressibility for the transition state of the same reaction. As for the negative compressibility of the transition state Walling and Tanner did not explicitly stated in their paper, then Hamann[33] proposed the term and considered it to be quite reasonable because of the unstable nature of the transition state. These authors treated only non-ionic systems. The negative compressibility of the transition state seems more probable in the system of oppositely charged reactants than in the non-ionic system.

Distribution of isomers

Pressure exerts possible factors which contribute to the orientation of substitution. For such factors, there are steric hindrance, electrostriction and cavity compression. In the case of chlorination of acetanilide in aqueous solution, the change of solvation is certainly the main factor among them, and predominates the simple steric factor.

In the possible case of steric hindrance as nitration of 1, 3-xylene, an increase in pressure tends to favor the formation of sterically compressed isomer. In the case of the nitration of toluene or chlorobenzene, however, the pressure effect almost arises from the changes of dielectric constant and solvation rather than steric hindrance[18].

Hamann[34] suggested that the co-operation of electron donating property of $-NHCOCH_3$ and the polarization of substituting chlorine might cause strong solvation for *para*-chlorination than for *ortho*-chlorination. Consequently, the difference between the solvation changes will benefit for *para*-chlorination under pressure.

Positive $\delta(JS_{\blacksquare}^{*})$ also suggest the lower degree of solvation of the intermediate complex for *ortho*-isomer than that for *para*-isomer.

Acknowledgments

The author is grateful to Prof. J. Osugi for his valuable suggestions and continuous encouragement and indebted to Dr. T. Asano for his helpful discussions and suggestions. The author also wishes to thank the visiting professor S. D. Hamann for his invaluable comments.

Laboratory of Physical Chemistry
Department of Chemistry
Faculty of Science
Kyoto University
Kyoto, Japan

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34) Private communication